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A Comparison of HF Digital Protocols

The world of HF digital communication is a confusing mix of protocols. Which offer the best performance?

In recent years our HF digital subbands have become Towers of Babel with several protocols competing for dominance. The familiar list includes AMTOR, G-TOR, CLOVER, PACTOR and PACTOR II.[1] Each mode has its enthusiastic supporters, but which ones are most efficient when it comes to transferring information?

The task of evaluating HF digital protocols is more than just an academic exercise. Our government has a stake in determining the answers because HF digital operators have traditionally supplied a large reservoir of backup communications services and operators during emergencies. In the interest of tapping this resource, the National Communications System (NCS) sponsored the National Telecommunication and Information Administration (NTIA) to test various HF modems and establish a technical baseline of standardized performance data on HF modem protocols. The Federal Emergency Management Agency (FEMA) will use those test results to determine which protocols could be used to serve as an interchange with the amateur community in the event of a national emergency. This article reflects the results of tests conducted at NTIA's Institute for Telecommunication Sciences (ITS) laboratories in Boulder, Colorado.

Solving the Propagation Problem

Many over-the-air tests have been conducted on various HF modem/protocol combinations. Atmospheric conditions vary so much, however, that it's impossible to draw solid conclusions. Over-the-air test results can change from day to day, or even hour to hour. To obtain scientifically valid information, you need stable conditions. Unfortunately, Mother Nature refuses to guarantee the stability of HF propagation!

So, we turn to the laboratory, where it's possible to create elaborate *simulations* of HF propagation paths. The engineers at ITS have developed an automated test bed for use in conducting controlled laboratory testing of modems and their protocols. Using this test bed, ITS subjected the protocols to a repeatable set of simulated propagation paths over a wide range of signal-to-noise ratios (S/Ns).[2]

Data transfers were performed at various S/Ns for each of the five protocols in their Automatic Repeat Request (ARQ) mode. All files received were checked for errors to determine the validity of the tests. The *throughput*, a measure of the data transfer rate, was measured for each protocol under simulated ionospheric conditions.

To conduct our tests we obtained HF modems manufactured by Kantronics, HAL Communications, Advanced Electronic Applications and SCS. However, specific models are not identified in this article. You'll see them referred to as modems A through D only. The intention is to evaluate protocols, not hardware. It is important to note that the use of specific hardware does *not* imply a recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the equipment used is necessarily the best available for this application.

Test Conditions

For each test, two identical modems (see Table 1), controlled and monitored by one 80486-based PC, were physically connected to each other by their audio-out/audio-in ports through two identical HF ionospheric channel simulators (Figure 1). Although the modems were both connected to the same PC, the operation of one was entirely independent of the other.

The modems were linked to the computer through the PC's serial communication ports (COM1 and COM2), except for the CLOVER

Table 1
HF Protocols Tested

Note: The AMTOR and PACTOR protocols were tested on two modems to determine if there were implementation differences in the results. The other three protocols were implemented by unique modems. Modems are identified simply as A, B, C and D.

Protocol	*Modem*	*Computer Interface*
AMTOR	A and B	Serial port
CLOVER	C	PC bus (plug-in card)
G-TOR	D	Serial port
PACTOR	A and B	Serial port
PACTOR II	A	Serial port

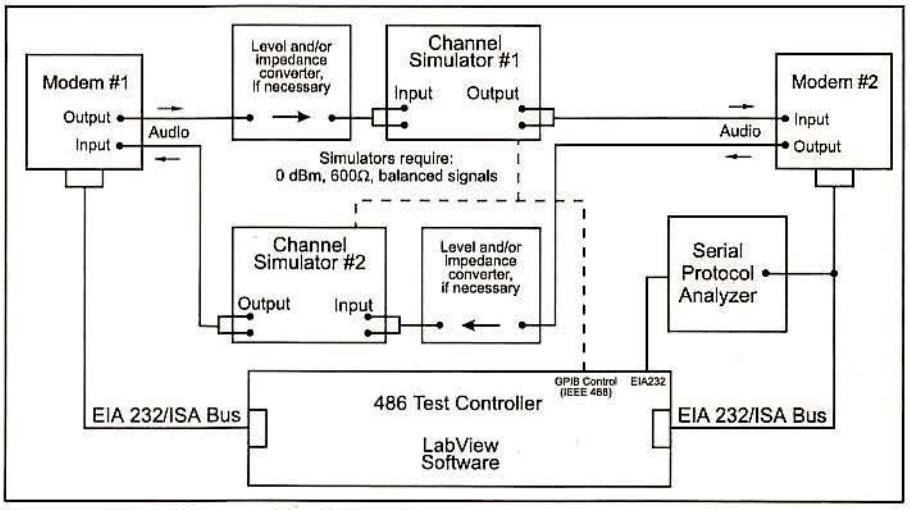

Figure 1—Block diagram of the HF modem test setup.

[1]Notes appear on page 39.

modem, which plugged into the PC's ISA bus. A *serial protocol analyzer* was used to monitor the serial port connection to the second (receiving) modem. A program running on the analyzer determined whether the test had timed out (no data had been transferred for a predetermined period of time). The test was controlled through the use of the National Instrument's program *LabView* (version 3.1.1), a *Windows*-based application capable of controlling, monitoring and measuring laboratory tests.

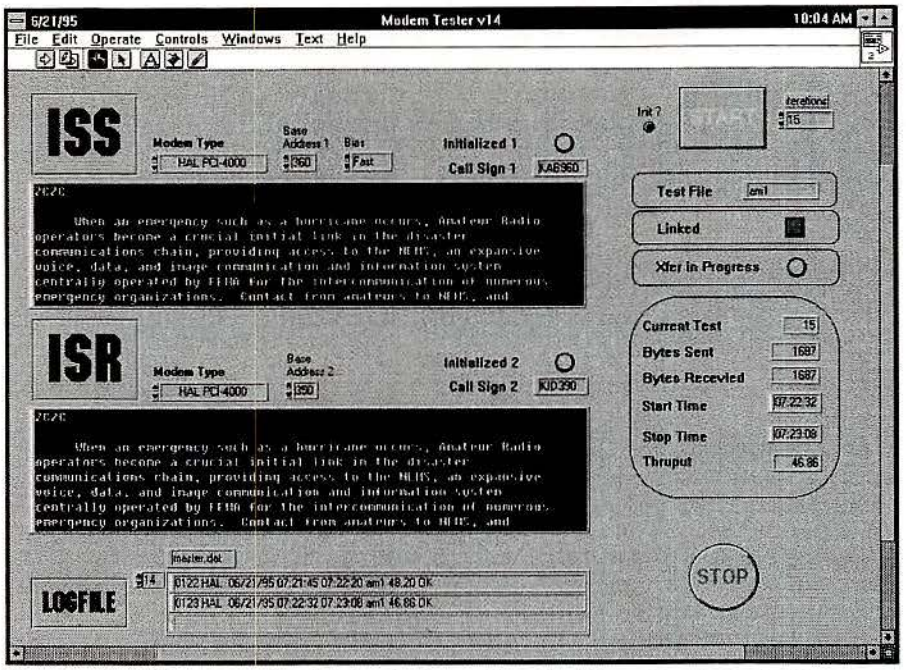

Figure 2—*LabView* generates this "control panel" on the PC monitor during testing.

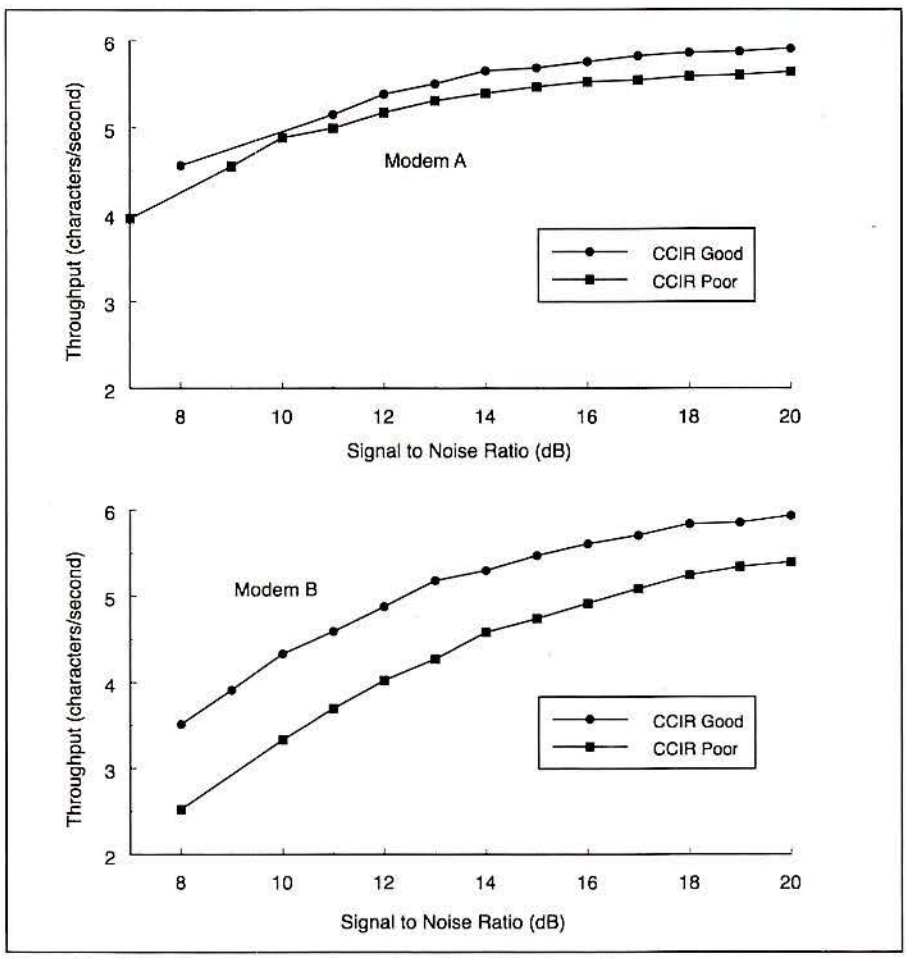

Figure 3—AMTOR protocol, modems A and B, CCIR Good/Poor

Two files were used to automate the test operation. The first was a test control file, containing a series of values representing the settings of the two simulators, the settings of the two modems and the file to be transmitted during each test. Results of the test were written to the second, a master log file.

For each test, *LabView* performed the following tasks:

1. Read the desired values of simulator settings, modem/protocol modes and parameters, and the file to be transmitted from the test control file.
2. Set the simulators to the desired values.
3. Initialized both modems to the desired mode.
4. Established a link between the two modems.
5. Started a timer.
6. Loaded the buffer of the transmitting modem with the test file.
7. Monitored the transmission and reception of the file.
8. Stopped the timer when the end-of-file was received.
9. Compared the received data to the original file to determine the success of the test.
10. Calculated the throughput and appended the test information to the master log file.
11. Flushed the modems' buffers in preparation for the next test.

LabView generated a front-panel display (Figure 2) that allowed the operator to monitor the progress of the test. This "panel" also supplied controls to permit the operator to run tests manually.

Which Parameters?

Because of the wide variety of protocols and the manner in which they are implemented, we didn't have enough time to test all possible parameter combinations. Because the goal of the tests was to determine the suitability of the modem/protocol combinations for use during emergency situations, we chose to test the protocols in their most robust mode. This meant testing only the ARQ mode. Because the ARQ mode is inherently error-free, there is no need to calculate error performance. Several of the protocols implemented algorithms for choosing modulation schemes. Otherwise, when manual settings were required, optimum settings were chosen based on the manufacturer's recommendations.

Seven or Eight Bits?

Because data can be transmitted in either 7 or 8-bit form, the type of test data used affects the throughput delivered by each protocol. Binary data and mixed-case ASCII data require a higher overhead when transmitted by a 7-bit protocol, thereby lowering the effective throughput. FEMA supplied a number of files it viewed as being "typical" traffic. These included both straight text and binary (word-processor format) content. To minimize the advantage 8-bit protocols have over 7-bit protocols, straight text files were chosen over binary files. When testing the

AMTOR protocol, which transfers data as 7-bit characters using the Baudot character set, an all-uppercase version of the test file was used. For the other protocols, which use 8-bit characters, a mixed-case version of the same file was used.

Compression

All of the HF modems we tested used some form of data compression, ranging from real-time Huffman compression to optimized Lempel-Ziv compression performed prior to transmission. In keeping with ITS's goal of choosing an optimum mode, compression was enabled throughout testing. However, this causes a sensitivity to the size of the data file, as well as to the type of data the file contains. Huffman compression operates on a small amount of buffered data, and is relatively insensitive to file size and large data patterns. The CLOVER protocol uses compression software licensed from PKWARE, which operates on the data prior to transmission. The PKWARE software implements several compression schemes and, since it operates on the file in its entirety, can result in a more efficient and sophisticated compression. Therefore, it is more effective with larger files. In light of these differences, a large file of 15,183 bytes, which should favor neither compression method, was chosen from the selection supplied by FEMA. When compression is used, the data being transmitted between the two modems is no longer strictly text, but includes nontext, binary values, regardless of the file's original content.

Simulated Propagation Conditions

The selected propagation conditions, based on the Watterson model, were "CCIR Poor" and "CCIR Good" (see Table 2). The S/N ranged from 0 dB to +20 dB (to +40 dB for CLOVER). Because the HF channel simulators are band-limited to a 5-kHz bandwidth, this was the reference bandwidth for measuring the S/N as recorded in the log file.

Baud Rate

Baud rate was another factor in modem performance. The different baud rates used for each protocol are summarized in Table 3. Often the modems available for testing dictated what baud rate could be used with a particular protocol. Most protocols have a baud rate at which they are commonly used or are legally permitted to be used, while some protocols automatically vary the baud rate, depending on conditions (as reflected by the received error performance). Some also vary the baud rate as a function of the modulation scheme. In all cases, the highest baud rate is limited by FCC bandwidth restrictions. Tests were performed at these typical baud rates, or the protocol was allowed to automatically select the rate.

The throughput, while related to baud rate, does not linearly correspond to it. Variations in overhead sizes (due to the use of error-detection and correction schemes), repeated transmissions, and variations in the number of bits representing a symbol make significant differences in the throughput of a file or message. Commonly used units of throughput are *characters per second* and *words per minute*. The throughput, in characters per second, reflects the amount of time needed to transmit a file under the conditions of noise, multipath propagation and fading. The characters-per-second rate is used because this relates to the actual time needed to transmit a file, and it includes the transmission overhead. Only tests in which the data was received error-free were included in the results.

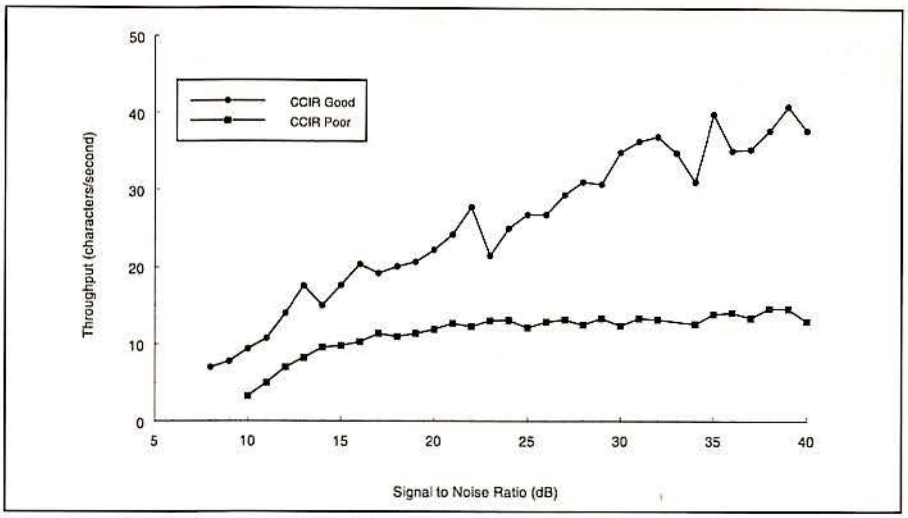

Figure 4—CLOVER protocol, CCIR Good/Poor

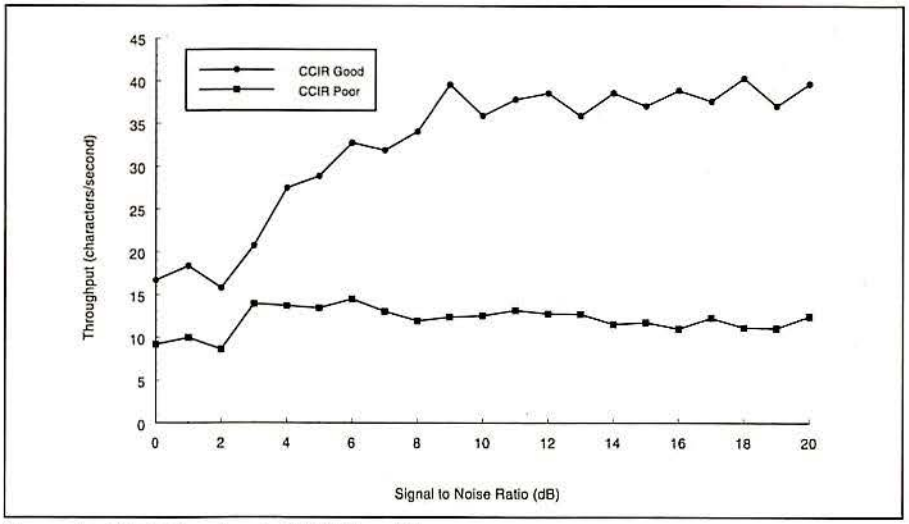

Figure 5—G-TOR protocol, CCIR Good/Poor

Table 2
Simulated Ionospheric Conditions Test Matrix for the Two-Path Watterson Model

Ionospheric Condition	*S/N (dB)*	*Fading Frequency Spread (Hz)*	*Multipath Delay (ms)*
CCIR Good	0 to +20 (to +40 for CLOVER)	0.1	0.5
CCIR Poor	0 to +20 (to +40 for CLOVER)	1.0	2.0

Test Limits and Time Constraints

Measurements over a clear channel (modems connected back-to-back without the simulators) were made to verify the modem setup and determine the optimal throughput. Table 4 presents the *clear-channel mean throughput* for each protocol and modem. Since implementations vary, one protocol can have significant differences in throughput between different models of modems. With this in mind, a protocol was tested on multiple modems whenever possible. This was the case with the AMTOR and PACTOR protocols only.

The clear-channel throughput was used to determine the limits of testing. While the ARQ mode will theoretically pass data error-

Table 3
Baud Rates Tested

Protocol	*Typical Baud Rates*	*Test Baud Rates*
AMTOR	100	100
CLOVER	92 to ~550	AUTO
G-TOR	100, 200, 300	AUTO
PACTOR	100, 200	200
PACTOR II	200 to 800	AUTO

Table 4
Clear Channel Mean Throughput

Protocol	*Clear Channel (optimal) Throughput (char/sec)*
AMTOR (modem A)	6.13
AMTOR (modem B)	6.26
CLOVER	45.60 (robust bias), 56.87 (normal), 69.05 (fast)
G-TOR	44.69
PACTOR (modem A)	25.46
PACTOR (modem B)	15.67
PACTOR II	133.53

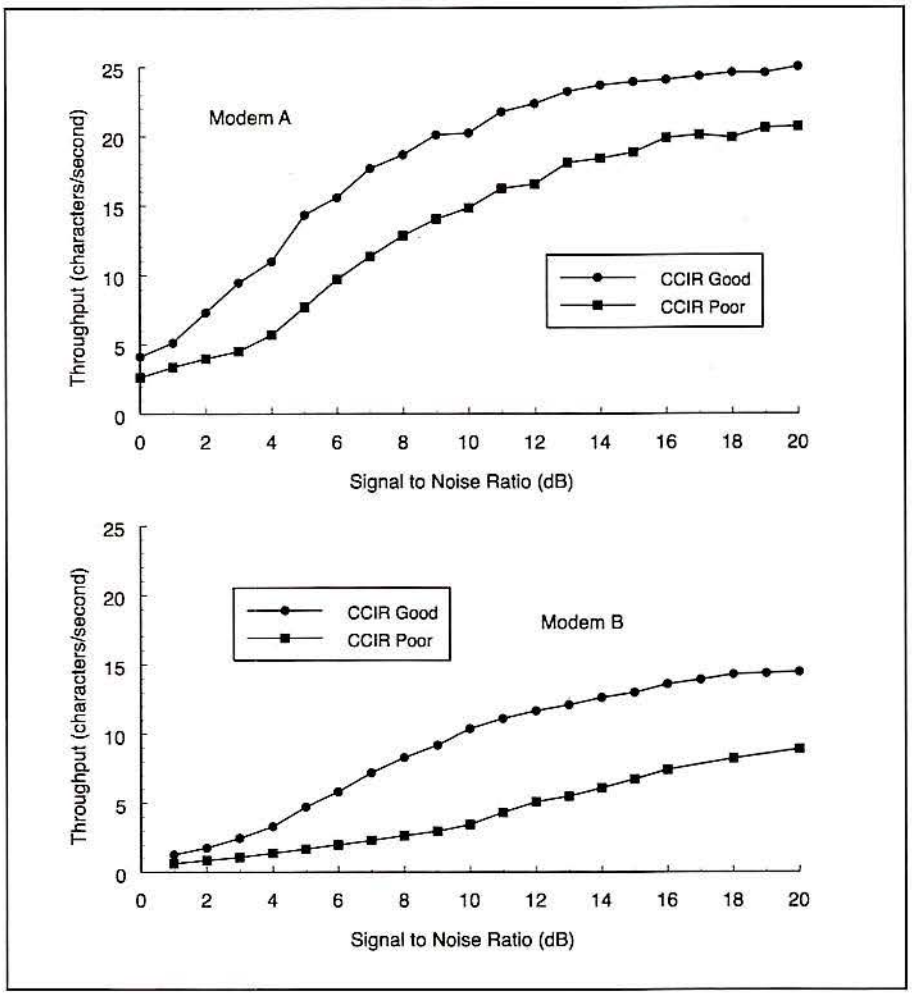

Figure 6—PACTOR protocol, modems A and B, CCIR Good/Poor

free, it also can require an unlimited number of retransmissions during poor signal conditions. Even under moderate conditions, occasional retries and associated handshaking will extend transmission time. As the transmission channel is degraded, the test time (time to pass a single data file) lengthens. At some point, the transmission time (and throughput) drops below a usable, practical level. Due to the limited time available to perform all of the desired tests, some breakpoint had to be set to restrict unnecessary testing. We decided to end testing when the throughput had dropped below 10% of its clear-channel value. While lower throughput may be usable in nonemergency situations, it is of little value during emergency situations, when rapid and reliable transmission of information is critical.

For an example of how time-consuming these tests are, consider the worst case: the AMTOR protocol. A suite of tests consists of 126 file transfers (21 transfers covering S/Ns of 0 dB to +20 dB in 1-dB increments, for two CCIR conditions, with three attempts each). At best, a throughput of six characters per second needed 42 minutes to transfer a 15,183-byte file, but as the S/N decreased, the transfer time increased. *Six days* were required to complete the AMTOR protocol suite of tests! This does not include the time needed to develop the drivers and initialization software necessary for each protocol/modem combination.

Results

The data collected during these tests is summarized in the plots in Figures 3 through 7. All plots display values of throughput (in characters/second) versus S/N (in dB).

The plots show the mean value of throughput for each S/N measured. The goal was to transmit a file three times for each S/N value. During development of the test procedure, more than three passes were made at certain settings. However, at low S/Ns, less than three passes are included in the plots due to errors and aborted tests. Again, the lack of time precluded us from running a test until three good completions were accomplished.

Over-the-Air Test Comparison

In 1993, FEMA ran a series of over-the-air tests as part of their program to evaluate new HF radio products.[3,4] Since FEMA and ITS tested two of the same modems and three of the same protocols, an attempt can be made to correlate the results of both tests.

FEMA chose frequencies characterized as either good or poor, based upon the *link quality analysis* (LQA) score supplied by an Automatic Link Establishment (ALE) transceiver, when such a score was available. When not available, RF output power was adjusted to simulate appropriate channel conditions. They estimated that a 10-dB S/N was the transition point between good and poor conditions. Tests were conducted across a network of three nodes at FEMA facilities in Berryville, Virginia; Denver, Colorado; and Urbana, Illinois; on frequencies authorized for FEMA use. A comparison of the FEMA tests to ITS's laboratory tests is shown in Table 5.

The LQA-based channel quality designators of "Good" and "Poor" do *not* correspond to the CCIR definitions for path conditions. Consequently, you can't make a direct comparison of data. Because the 10-dB breakpoint between LQA Good and LQA Poor is only an estimate, it's difficult to split up the laboratory measurement to approximate the LQA conditions. Therefore, a generalized comparison between the range of throughputs measured in the lab to the numbers obtained in the field is made, subject to these caveats.

The SITOR protocol was not tested in the lab because SITOR is a military version of the AMTOR protocol. While some differences in the two protocols may exist, ITS decided to drop SITOR from the tests, again due to time constraints. However, the SITOR field results are reasonably close to the AMTOR lab results. PACTOR II had not been introduced at the time of the 1993 tests.

In general, higher throughputs were recorded in the laboratory tests than in the field tests. The laboratory tests allowed for very high S/Ns that would reflect optimum (if not unrealistic!) real-world conditions and were not affected by the rapidly changing iono-

Table 5
FEMA Over-the-air Performance Test Results

Protocol/mode	*Compressed Data*	*File size (bytes)*	*Channel Quality*	*Over-the-air Throughput (char/sec)*	*ITS Lab Throughput (char/sec)*
SITOR ARQ	No	650	Good	4.42	3.9-5.9
			Poor	4.27	
PACTOR ARQ	No	650	Good	9.70	Not measured
			Poor	5.70	
PACTOR ARQ	Yes	650	Good	8.80	2.5-25.0
			Poor	Not measured	
CLOVER ARQ	Yes	3238	Good	28.03	7.0-40.0
			Poor	16.83	

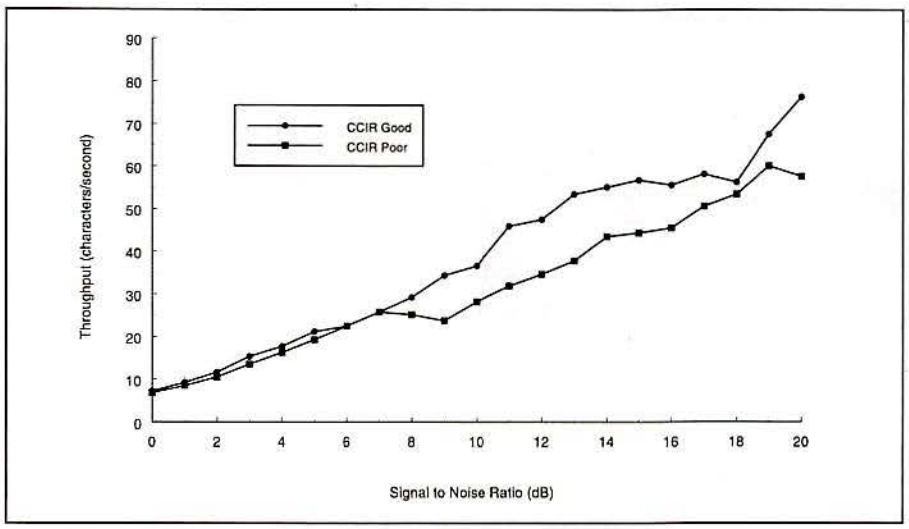

Figure 7—PACTOR II protocol, CCIR Good/Poor

spheric conditions that challenge real HF operations. However, for providing a useful performance baseline of protocol performance, the laboratory tests are preferred. They can be repeated at any time of day or year, ensuring that the conditions will be the same for all tests.

Conclusions

In the case of CLOVER, the results show the obvious effects of phase modulation, automatic modulation selection, and the use of a sophisticated compression scheme. Throughput is notably dependent on file size and, although not tested, content. Compared to its clear-channel performance, the use of phase modulation demonstrates a susceptibility to multipath distortion. As the throughput varies, CLOVER changes phase modulation schemes (BPSM at low rates, through QPSM, 8PSM, 8P2A, 16PSM, to 16P4A at high rates) which shows up as points of discontinuity in the plotted data, notably at the 12, 23 and 35-character/second points.

CLOVER also uses a Reed-Solomon error-correction algorithm, the efficiency of which can be set to three levels (*Robust*, where 60% of the transmitted block contains data; *Normal*, 75%; and *Fast*, 90%). The Fast bias setting, which produced the highest throughput, was used during testing. Based on the test data, CLOVER seems to be best suited for transmitting large files. Note that the CLOVER protocol was tested over a S/N range of 0 to +40 dB, at the insistence of the manufacturer. All of the other protocols were tested over a range of 0 to +20 dB.

Similar results appear for the PACTOR II protocol, which also uses phase modulation, although the selection of phase level (DBPSK, DQPSK, 8-DPSK and 16-DPSK) is done manually, and not automatically as with the CLOVER protocol. For testing, the highest transfer rate (corresponding to the highest phase level modulation [16-DPSK]) was chosen. In both CLOVER and PACTOR II, the highest throughput measured under CCIR Good conditions is nearly half of the clear-channel throughput, and rolls off quicker for decreasing S/Ns than does the throughput of protocols that do not use phase modulation schemes. However, the throughput of these two protocols is an order of magnitude greater than the "basic" AMTOR protocol.

An attempt was made to determine if the throughput of a particular protocol was specific to the manufacturer's implementation, or whether it was representative of all modems using that protocol. Of the five protocols tested, PACTOR and AMTOR are the most popular among amateur HF digital operators. CLOVER and G-TOR are proprietary protocols implemented by their respective developers only. PACTOR II is beginning to appear in modems produced by a couple of manufacturers. But at the time these tests were performed, only one manufacturer was shipping units. Consequently, multiple testing was performed only on the PACTOR and AMTOR protocols.

The throughputs of PACTOR and AMTOR were measured on two modems from different manufacturers. As can be seen in the plots in Figures 3 and 6, there is a difference in the two implementations of each protocol. In the case of PACTOR, the difference is significant; the throughput of modem A is nearly twice that of modem B even though the test conditions were identical for both modems. No attempt was made to determine why this difference existed, but it raises questions regarding interoperability of modems from different manufacturers using a common protocol.

In testing the two implementations of the AMTOR protocols, functional differences emerged during the test development phase. One modem appeared to transmit only those characters contained in the BAUDOT character set. Undefined characters were received as a question mark. The other modem could transmit additional (punctuation) characters, apparently using the character positions the BAUDOT set listed as undefined. This could cause problems when trying to communicate between these two modems over a mixed-modem link. While AMTOR is not an appropriate protocol for use in transferring binary data or heavily formatted text, the incorrect transfer of certain punctuation characters could corrupt the meaning of a text message.

Obviously, more extensive testing must be done before a single protocol can be recommended for use by FEMA. Before that is done, the overall requirements, including the range of channel conditions and the characteristics of the traffic (content, size and frequency of transmission), must be better defined.

Notes

[1]No doubt you'll notice that HF packet is missing from the list. Although it is popular on VHF and above, packet is often a poor choice for HF communication. This protocol is not particularly robust. It requires excellent signals at both ends of the path and also stable conditions for reasonable efficiency. With this in mind, HF packet was eliminated from consideration as a "serious" contender.

[2]Two narrowband, Watterson model HF propagation channel simulators created the ionospheric propagation conditions for each test. Two degraded conditions were used: CCIR *Good* and CCIR *Poor*.

[3]H. F. Wetzel, "HF Modem Over-the-Air Performance Test Report, Globe Link Corporation HF Modem Model GLC-1000A," Federal Emergency Management Agency, Washington, DC.

[4]H. F. Wetzel, "HF Modem Over-the-Air Performance Test Report, HAL Communications PCI-4000 HF Modem," Federal Emergency Management Agency, Washington, DC.

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